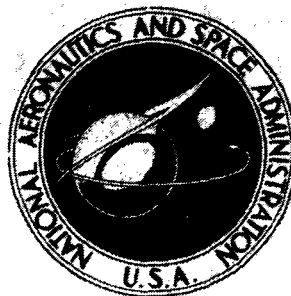


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**CREEP-RUPTURE TESTS
OF INTERNALLY PRESSURIZED
RENÉ 41 TUBES**

by Klaus H. Gumto and Barry Weiss

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16. Abstract Weld-drawn tubes of René 41 with 0.935-centimeter (0.375-in.) outside diameter and 0.064-centimeter (0.025-in.) wall thickness were tested to failure at temperatures from 1117 to 1233 K (1550 ⁰ to 1760 ⁰ F) and internal helium pressures from 5.5 to 12.4 meganewtons per square meter (800 to 1800 psi). Lifetimes ranged from 5 to 2065 hours. The creep-rupture strength of the tubes was 50 percent lower than that of unwelded, thick sheet specimens, and 20 percent lower than that of unwelded, thin sheet specimens. Larson-Miller correlations and photomicrographs of some specimens are presented.					
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SUMMARY

In order to obtain creep-rupture data for designing a helium-to-air heat exchanger, 33 weld-drawn René 41 tubes were tested to failure at constant temperature and pressure. The tubes were pressurized internally with helium but were tested in an air atmosphere.

Tubes with 0.953-centimeter (0.375-in.) outside diameter and 0.064-centimeter (0.025-in.) wall thickness were purchased. René 41 is a nickel-base superalloy and was selected for its high strength at high temperatures, its fabricability, and its resistance to oxidation and corrosion.

The test temperatures and pressures were chosen to simulate the proposed service conditions. The test temperatures ranged from 1117 to 1233 K (1550⁰ to 1760⁰ F), with helium pressures from 5.5 to 12.4 meganewtons per square meter (800 to 1800 psi) corresponding to equivalent stresses from 38.51 to 91.05 meganewtons per square meter (5.59 to 13.21 ksi). The lifetimes for the tubes ranged from 5 to 2065 hours.

The test pressures were converted to equivalent stresses, which were correlated with lifetimes and test temperatures by the Larson-Miller parameter. The tubes all failed in the weld zone. Comparison of the creep-rupture data for the tube specimens with the data for unwelded sheet specimens showed that the rupture strength of the tubes was 20 percent lower than that of the thin sheet specimens and 50 percent lower than that of the thick sheet specimens.

To demonstrate the application of the test results, the lifetime of a tube with a 0.635-centimeter (0.250-in.) outside diameter and a 0.076-centimeter (0.030-in.) wall thickness was calculated. This tube had an internal pressure of 10.3 meganewtons per square meter (1500 psi) and a temperature of 1089 K (1500⁰ F). For these conditions, and with a safety factor of 1.5, the predicted lifetime is 4300 hours.

INTRODUCTION

One of the mobile nuclear powerplants proposed for both air-cushion vehicles (ref. 1) and aircraft (ref. 2) consists of a helium-cooled nuclear reactor and a helium-to-air exchanger. The heat exchanger is located in the combustor section of an aircraft turbofan engine. This powerplant will be designed to operate 10 000 hours before overhaul and refueling. The helium-to-air heat exchanger will be operating at temperatures up to 1144 K (1600° F) and pressures up to 12.41 meganewtons per square meter (1800 psi).

The creep-rupture properties of the candidate heat-exchanger material must be known in order to make the heat exchanger as light as possible for a lifetime of at least 10 000 hours. The behavior of the material under multiaxial stress conditions, such as the conditions in the walls of a pressurized tube, may be predicted by yield criteria such as those of von Mises or Tresca. Such methods use uniaxial test data and assume that the material is isotropic. The yield criteria, however, do not accurately predict the behavior of an internally pressurized tube tested at high temperatures over a long period of time, because tubes become anisotropic during their manufacture.

In order to provide data for a heat-exchanger design, tests were performed on candidate heat-exchanger materials. Internally pressurized tubes were tested in furnaces at conditions selected to simulate the proposed heat-exchanger environment.

One of the materials selected as a candidate was René 41. This is a nickel-base superalloy, and is available commercially in weld-drawn tube form. This alloy was chosen because it is one of the strongest of the wrought, nickel-base superalloys at the engine operating conditions. This rank is based on a comparison of uniaxial tensile-test data for the nickel-base superalloys. Beside its high strength, the alloy is also oxidation resistant and can be welded and fabricated.

The test results were correlated with the same method the author used in reference 3. This method assumes that the von Mises yield criterion holds for creep strain, that the secondary creep rate is a power function of stress, and that for long lifetimes, primary and tertiary creep may be neglected. The test results are presented in tabular form and by means of stress-parameter plots.

All measurements were made in U.S. customary units.

SYMBOLS

- B material constant
- n stress exponent
- P Larson-Miller parameter

p	pressure, MN/m^2 (psi)
T	temperature, K ($^{\circ}\text{F}$)
t	time, hr
$\dot{\epsilon}$	strain rate, hr^{-1}
$\dot{\epsilon}_{\theta a}$	diametral strain rate at the bore of the tube, hr^{-1}
$\dot{\epsilon}_{\theta b}$	diametral strain rate at outside diameter of tube, hr^{-1}
$\dot{\bar{\epsilon}}_a$	equivalent strain rate at the bore of the tube, hr^{-1}
ρ	ratio of the outside diameter to the inside diameter of the tube
$\bar{\sigma}$	equivalent stress, MN/m^2 (ksi)

PROCEDURES

Material

Thirty-three weld-drawn tubes of René 41 (refs. 4 and 5) were tested. This alloy is a nickel-base superalloy. Because it is oxidation resistant and has high strength at high temperatures, this alloy is used for afterburners and other jet-engine parts exposed to high temperatures. The high strength in the temperature range of 922 to 1255 K (1200° to 1800° F) is developed by solution and aging heat treatments. René 41 is hardened by precipitation of titanium and aluminum compounds as well as by the solid-solution strengthening due to nickel, chromium, cobalt, and molybdenum.

The commercially purchased tubes were roll formed, welded, and drawn to size with intermediate anneals. The tubes were then solution treated at 1340 to 1450 K (1950° to 2150° F) and aged at 1033 K (1400° F) for 16 hours, followed by air cooling.

Table I lists the chemical analyses of several samples as well as the Aeronautical Material Specification for René 41. An independent laboratory performed the analysis for the tube specimens.

Test Specimens

The René 41 tube specimens were from 35.6 to 40.6 centimeters (14 to 16 in.) long, with a nominal outside diameter of 0.953 centimeter (0.375 in.), and a wall thickness of 0.064 centimeter (0.025 in.). Table II shows the measured outside diameter and wall thickness of each tube. The tube length was chosen so that the welded ends of the tube specimens remained outside the 30.5-centimeter- (12-in.-) long test section of the fur-

nance. The ratio of tube diameter to wall thickness was about 15, which classifies these specimens as thick tubes.

Each tube-specimen test assembly (fig. 1) was fabricated with gas tungsten-arc welds. The materials were first ultrasonically cleaned and degreased. The end plug and inlet fitting, made from Inconel, and the hanger wire and the inlet tube with sleeve and sleeve nut, made from 304 stainless steel, were welded in place. Finally, the completed tube specimens were tested with a mass spectrometer to ensure that the welds were helium tight.

Tests

Figure 2 is a schematic of the tube test rig. Four tubes at a time were tested in one of the electric resistance furnaces in an air atmosphere. The tubes were tested at constant temperatures and static internal helium pressures until failure. Three Chromel-Alumel thermocouples located at the middle and ends of the 5-centimeter- (2-in.-) long, constant-temperature zone (± 1.7 K ($\pm 3^{\circ}$ F)) measured the test temperatures, which were recorded on a 24-channel strip-chart recorder. The thermocouples were suspended from the top of the furnace and were not attached to the test specimens. The test pressures were monitored by a pressure transducer in the pressure circuit of each specimen and were recorded continuously on a second 24-channel strip-chart recorder.

Before the test, the tubes were pressurized with helium to about 8.3 meganewtons per square meter (1200 psi), followed by a release of the pressure. Several cycles of this procedure purged the tubes of air. After this, the furnaces were brought up to the test temperatures. When the temperatures had stabilized, each tube was pressurized with helium to its test pressure and was then sealed off by means of a valve. The pressures were monitored daily to check for minor leaks and tube failures. If small leaks in the system other than in the test specimen caused loss of pressure, helium was added as required to maintain the test pressure. A pressure drop to 1/3 of the test pressure in less than 48 hours constituted failure.

The helium test pressures ranged from 5.5 to 12.4 meganewtons per square meter (800 to 1800 psi), the temperatures ranged from 1117 to 1233 K (1550° to 1760° F), and the test times varied from 5 to 2065 hours. The effective stresses at the tube bore were from 38.51 to 91.05 meganewtons per square meter (5.59 to 13.21 ksi). The tests were run in furnace air to observe the effects of metallurgical changes and oxidation on life.

Metallography

Sections of the tubes were taken both before and after testing, in both the longitudinal and transverse direction. For the post-test specimens, the sections were taken near the point of failure. The surfaces of the sections were etched electrolytically with 10-percent chromic acid except for the as-received specimens before testing, which were etched with 92-5-3 (92 percent HCl, 5 percent H₂SO₄, 3 percent HNO₃).

Accuracy

The uncertainty in the specimen temperature was about ± 2.8 K ($\pm 5^{\circ}$ F). The furnace controller sensitivity of ± 2 microvolts and thermocouple variations contributed to the temperature uncertainty. The accuracy of the specimen pressures was estimated at ± 0.07 meganewtons per square meter (± 10 psi). This accuracy was affected by small leaks in the system, by daily variation in the room temperature, and by expansion of the tube due to creep. The variation of the tube wall thickness was ± 1.2 percent.

Analysis

The analysis of the tube test data was described in detail in reference 3, and it is based on the following assumptions:

- (a) The tube material is isotropic.
- (b) The von Mises criterion for yielding is applicable to creep in the pressure tube wall.
- (c) The principal strain rates are proportional to the reduced, or deviatoric, principal stresses (ref. 6).
- (d) The axial strain rate is zero.
- (e) The principal axes of stress and creep strain coincide.
- (f) Norton and Bailey's exponential stress law, presented in reference 7, applies.

$$\dot{\epsilon} = B\bar{\sigma}^n \quad (1)$$

(g) The strain rate remains uniform over the life of the specimen; that is, primary and tertiary creep are negligible compared with secondary creep. Therefore, the diametral strain rate $\dot{\epsilon}_{\theta b}$ is equal to the strain measured on the outside diameter at rupture divided by the lifetime of the specimen.

On the basis of these assumptions, the following equations are used in the analysis. The equivalent stress at the bore of the tube is

$$\bar{\sigma} = \frac{\frac{\sqrt{3}}{2} \rho^{2/n}}{\rho^{2/n} - 1} p \quad (2)$$

The diametral strain rate at the tube bore is related to the strain rate at the outside diameter by

$$\dot{\epsilon}_{\theta a} = \rho^2 \dot{\epsilon}_{\theta b} \quad (3)$$

The equivalent strain rate at the bore of the tube is

$$\dot{\bar{\epsilon}}_a = \frac{2}{\sqrt{3}} \rho^2 \dot{\epsilon}_{\theta b} \quad (4)$$

Strain Measurement

The difference of the diameters of the failed and as-received tubes divided by the diameter of the as-received tube measured the circumferential strain at fracture. The outside diameters were measured, both before and after the test, with a micrometer at four points spaced 45° apart on each tube circumference. The measurements before the test were made at the middle of the tube. Following the tests, the tubes were measured at the point of fracture. Each set of four measurements was averaged to obtain the as-received and the strained diameters.

The diameters were also measured at a point 2.5 centimeters (1 in.) from the inlet end of the tube. Since this point was outside the furnace, no change was expected here. Comparison of measurements before and after the test show this to be so. This check was necessary because the tube wall thickness could not be measured before the test. Therefore, the tube was cut apart following the test and the wall thickness was measured with a caliper type micrometer at 2.5 centimeters (1 in.) from the inlet end at four places spaced 45° apart. The four measurements were averaged to obtain the tube wall thickness.

RESULTS AND DISCUSSION

Thirty-three creep-rupture test specimens were fabricated from commercially purchased, weld-drawn, René 41 tubing. The specimens were pressurized internally with helium and tested in an electric resistance furnace at constant temperature in an air atmosphere at atmospheric pressure. The internal helium pressures ranged from 5.5 to 12.4 meganewtons per square meter (800 to 1800 psi), while the test temperatures ranged from 1117 to 1233 K (1550° to 1760° F). The effective stresses at the tube bore varied from 38.51 to 91.05 meganewtons per square meter (5.59 to 13.21 ksi), and the lifetimes ranged from 5 to 2065 hours. The test results are listed in table III.

Correlation

The equivalent stresses and the Larson-Miller parameter values are shown in table III and figures 3 and 4 for the tubes, and in table IV and figures 4 and 5 for the unwelded sheet creep-rupture data. The equivalent stresses were calculated by using equation (2), which gives the equivalent stress at the tube bore by the distortion energy theory.

The values of the stress exponent n used in equation (2) are a function of temperature and are listed in table II. The values used in this report ranged from 5.39 at 1117 K (1560° F) to 2.38 at 1233 K (1760° F). The method used to calculate n was described in reference 3.

The unwelded René 41 sheet data from reference 8 covered sheet thicknesses from 0.015 to 0.318 centimeter (0.006 to 0.125 in.). The sheets with thicknesses of 0.015 and 0.025 centimeter (0.006 and 0.010 in.) are referred to as thin sheets in this report. The remainder of the sheets, with thicknesses of 0.063 to 0.318 centimeter (0.025 to 0.125 in.), are referred to as thick sheets.

The test results for the tubes and the sheet materials were used as input for the computer program of Mendelson, Roberts, and Manson (ref. 9). This program correlated the stress, lifetime, and temperature data by means of the Larson-Miller parameter. The program selected a parameter constant of 14.733 for the tubes and 16.810 for the combined thick and thin sheet specimens. The results are plotted in figures 3 and 5, which show the fitted parameter curves with ± 1 standard deviation.

Since the parameter constants for the tubes and sheets were different, a direct comparison would not be meaningful. In order to make a comparison, the test results and the uniaxial sheet test data were correlated by means of the Larson-Miller parameter by using a constant of 20.0. This is a commonly used value and therefore permits comparison with other published data that also use this constant. The results of the computer calculations are listed in tables III and IV and are shown in figure 4. This figure

shows that the rupture strength of the tubes for a given value of P is about 20 percent lower than that of the thin sheet creep-rupture specimens (ref. 8) and about 50 lower than the thick sheet specimens.

A sample calculation to predict the lifetime of a tube under given temperature and pressure conditions based on the test results is shown in the appendix.

Creep-Strain Rate

The creep-strain rate was obtained by first measuring the diametral strain at rupture, then calculating the equivalent bore strain, and finally dividing the bore strain by the lifetime of the tube. The equivalent bore-strain rates obtained by this method are listed in table III. It should be noted that this method assumes that the creep-strain rates are uniform over the lifetime of the specimens and that the primary and tertiary creep is negligible compared with secondary creep, so that the resultant creep-strain rates are average values. This method also assumes uniform strain around the periphery of the tube. This is probably not the case because of the welds. Table IV lists the creep-strain rates for the uniaxial test specimens calculated from the test results reported in reference 8.

Fracture

All specimens failed in the weld area of the tube wall. The fracture occurred on radial planes parallel to the tube axis. The failure area was large enough to be identified by the unaided eye. A bubble leak test was performed, however, in order to verify the leak location. The failures are similar to those reported by Morris (ref. 10) for weld-drawn N-155 tubes. The pressure drop following failure was more rapid than the drop observed for the seamless tubes of Haynes Alloy No. 25 (ref. 23). The time to drop to one-third of the test pressure following the fracture ranged from 5 to 690 minutes, with most of the tubes falling into the 5- to 60-minute range.

Metallography

Figures 6 to 8 are photomicrographs of tube specimens both before and after the test, showing both longitudinal and transverse sections. The original photomicrographs were magnified 100 to 125 times, as indicated on the photographs.

Figures 6(a) and (b) show a tube in the as-received condition. Figure 6(a) shows both the weld area and the parent metal. The weld area has a cast structure, while the

parent metal has a wrought structure. The photograph shows no γ' ($\text{Ni}_3(\text{Ti}, \text{Al})$) phase, which indicates that the tubes were heat treated above the γ' solution temperature of about 1330 K (1930° F). The carbides (probably $\text{Fe}_2\text{W}_2\text{C}$ (ref. 11)) appear as stringers in the direction of work during the manufacturing process. A hardness test on the transverse section resulted in a Rockwell C hardness of 23 in the weld area and 21 in the parent metal.

Figures 7(a) and (b) show the tube specimen 25 after 195 hours at 1172 K (1650° F) and 8.27 meganewtons per square meter (1200 psi). Figure 7(a) shows a transverse section of the weld area, including the fracture. The cast structure seen in figure 6(a) has changed to the grain structure associated with wrought material. The entire weld area wall thickness has been reduced about 20 percent due to straining (necking down). The section also shows precipitation at the grain boundaries, which is probably the M_6C carbide as $\text{Fe}_2\text{W}_2\text{C}$ and μ phase (Co_7Mo_6) (ref. 11).

Figure 7(b) shows the longitudinal section of the parent metal. The grains, showing the γ' phase within, did not change in size. The tube wall thickness remained the same. The inner and outer surface of the tube, as well as the fracture surface, show a lighter region indicative of a depletion zone. Some oxidation is also evident in this zone.

The depletion and oxidation on the inside of the tube resulted from the fact that the specimen remained in the furnace for a relatively long time after it had failed. The specimen failed at 195 hours. Following the loss of pressure, air diffused through the rather large fracture. The tube remained in the furnace for about 300 hours more, until the last specimen in the furnace had failed, resulting in a total time at temperature of about 500 hours. By comparison, figure 8 shows a specimen which was the last to fail in its furnace, so that no depletion and oxidation occurred at the inner surface.

A hardness test on the longitudinal section shown in figure 7(b) gave a Rockwell C hardness of 39 in two places in the parent metal, 26 in the depletion region at the inside diameter, and 33 in the depletion region at the outside diameter. The increase in hardness over the as-received metal (Rockwell C 21) is probably due to strengthening by γ' precipitation.

Figures 8(a) and (b) show tube specimen 1 after 2065 hours at 1117 K (1550° F) and 7.93 meganewtons per square meter (1150 psi). Again, figure 8(a) is a transverse section through the failure region in the weld area. The oxidation and depletion zones are visible only near the outside diameter because specimen 1 was cooled to room temperature immediately after loss of pressure, so that no oxidation was possible on the inside surface. Large cracks appear to have started at the outside diameter in the depletion zone. The failure area contains a number of voids, and the wall thickness here has been reduced by about 27 percent by straining. The structure of the material in the weld area has changed similarly to that in figure 7(a), and a large amount of a white appearing precipitate is visible at the grain boundaries.

Figure 8(b) shows a longitudinal section through the parent metal after the test. Grain growth and reduction of wall thickness are not apparent. As in figure 7(b), the grain interiors have a dark γ' precipitate and the stringers have disappeared. The oxidation and depletion zones are visible at the outside diameter. A hardness test resulted in a Rockwell C hardness of 39 in two locations in the parent metal and 33 in the depletion zone at the outside diameter.

CONCLUDING REMARKS

Thirty-three weld-drawn tubes of René 41, pressurized internally with helium, were tested in an electric resistance furnace until failure. The tests in an air atmosphere ranged from 5 to 2065 hours. The test temperatures ranged from 1117 to 1233 K (1550° to 1760° F), and the pressures ranged from 5.5 to 12.4 meganewtons per square meter (800 to 1800 psi). The pressures resulted in equivalent stresses at the tube bore of 38.51 to 91.05 meganewtons per square meter (5.59 to 13.21 ksi). The pressures were converted to equivalent stresses and correlated to the test temperatures and lifetimes by the Larson-Miller parameter. The parameter constant for the tubes and the sheet creep-rupture test specimens was selected by a computer program. A graph is shown for the sheet and the tube correlation. Both sets of data were also correlated by the Larson-Miller parameter with a constant of 20.0, which permits both sets to be presented on one graph for comparison.

Analysis of the test data and the photomicrographs produced the following results and conclusions:

1. Tests of the weld-drawn, René 41 tubes showed that the creep-rupture strength was about 50 percent lower than that of thick sheets, and about 20 percent lower than that of thin sheets.
2. Reliable predictions of creep-rupture lifetimes for weld-drawn, René 41 tubes under given temperature and stress conditions cannot be made on the basis of unwelded sheet creep-rupture data.
3. Failures of welded René 41 tubes occurred in the weld zone only where the fracture started at the outside surface and propagated radially inward.
4. Large strains and failures in the weld zone, combined with very little strain (as indicated by reduced wall thickness due to necking down) and no failures in the parent metal, indicate that the creep-rupture tests measured the strength of the weld metal only. Therefore, the results of this report should not be applied to seamless tubes of René 41, which can be expected to have greater creep-rupture strength.
5. If creep-rupture lifetime predictions for tubes must be based on sheet creep-rupture data, results from tests of thin sheets (sheet thickness about the same as the

tube wall thickness) will yield better predictions than results from thick sheets (sheet thickness more than twice the tube wall thickness).

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, November 29, 1971,
132-15.

APPENDIX - APPLICATION OF DATA

One example of the application of the creep-rupture data is the calculation of the service lifetime for tubes in a heat exchanger at a constant temperature and a constant internal pressure. The following are the pertinent specifications and conditions for a weld-drawn, René 41 tube used in the sample calculations:

Material	René 41, weld-drawn tubing
Tube size:	
Outside diameter, cm (in.)	0.635 (0.250)
Wall thickness, cm (in.)	0.076 (0.030)
Ratio of outside diameter to inside diameter	1.3158
Pressure, MN/m ² (psi)	10.3 (1500)
Temperature, K (°F)	1089 (1500)
Stress exponent n	5.9
Safety factor N	1.5

The equivalent stress is calculated by equation (2):

$$\bar{\sigma} = \frac{\frac{\sqrt{3}}{5.9} (1.3158)^{2/5.9}}{(1.3158)^{2/5.9} - 1.0} p = 3.30 p = 34.04 \text{ MN/m}^2 \text{ (4957 psi)}$$

The ultimate equivalent strength $\bar{\sigma}_u$ is calculated by

$$\bar{\sigma}_u = N\bar{\sigma} = 1.5 \bar{\sigma} = 51.06 \text{ MN/m}^2 \text{ (7435 psi)}$$

The parameter value of 36.0 for the equivalent stress of 51.06 MN/m² (7435 psi) is obtained from figure 3, and the parameter equation is solved for the lifetime t:

$$t = \text{antilog} \left(\frac{1000 P}{1.8 T} - 14.733 \right) = 4300 \text{ hours}$$

where temperature T is in K. Thus, for the given conditions, the service lifetime is 4300 hours. The calculated lifetime for a tube without the safety factor is 14 800 hours.

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TABLE I. - CHEMICAL COMPOSITION OF SPECIMENS OF RENÉ 41

[Composition in weight percent.]

Component	Aeronautical Material Specification, AMS 5545	Specimen				
		Heat T3-8458 tubes (a)	NEM063 (b)	PW093 (b)	MQC064 (b)	DMS006 and DMS010 (b)
Nickel	Balance	52.00	Balance	Balance	Balance	Balance
Chromium	18.0 to 20.0	19.55	19.22	18.7	18.6	19.06
Cobalt	10.0 to 12.0	11.31	11.03	(c)	10.98	11.33
Molybdenum	9.0 to 10.5	9.95	9.73	9.83	9.84	9.87
Iron	0 to 5.0	2.36	(c)	2.05	.57	1.55
Titanium	3.0 to 3.3	2.96	3.2	3.2	3.11	3.12
Aluminum	1.4 to 1.6	1.60	1.5	1.58	1.48	1.52
Silicon	0 to 0.5	.12	(c)	(c)	(c)	(c)
Carbon	0 to 0.12	.09	.07	.10	.10	.08
Manganese	0 to 0.10	.06	(c)	(c)	(c)	(c)
Boron	0.003 to 0.01	(c)	.004	.004	.01	.006

^aAnalysis by an independent laboratory.

^bSheet tensile specimens from reference 8.

^cNot reported.

TABLE II. - TEST DATA FOR RENE 41 TUBES

Specimen	Temperature, T		Pressure, p		Lifetime, hr	Outside diameter				Wall thickness		Stress exponent, n
	K	°F	MN/m ²	ksi		Before test		After test		cm	in.	
						cm	in.	cm	in.			
1	1116.5	1550.0	7.93	1.15	2065.0	0.9611	0.3784	1.0226	0.4026	0.0571	0.0225	5.39
2	1116.5	1550.0	8.27	1.20	898.0	0.9553	0.3761	0.9888	0.3893	0.0561	0.0221	5.39
3	1116.5	1550.0	9.65	1.40	1093.0	0.9535	0.3754	0.9817	0.3865	0.0559	0.0220	5.39
4	1116.5	1550.0	9.65	1.40	1077.0	0.9606	0.3782	0.9982	0.3930	0.0589	0.0232	5.39
5	1116.5	1550.0	10.34	1.50	648.0	0.9601	0.3780	1.0005	0.3939	0.0589	0.0232	5.39
6	1116.5	1550.0	10.34	1.50	341.0	0.9566	0.3766	0.9942	0.3914	0.0559	0.0220	5.39
7	1116.5	1550.0	10.34	1.50	374.0	0.9588	0.3775	1.0102	0.3977	0.0589	0.0232	5.39
8	1116.5	1550.0	10.34	1.50	354.0	0.9594	0.3777	1.0058	0.3960	0.0589	0.0232	5.39
9	1116.5	1550.0	11.03	1.60	553.0	0.9578	0.3771	1.0025	0.3947	0.0584	0.0230	5.39
10	1116.5	1550.0	11.03	1.60	436.0	0.9591	0.3776	0.9809	0.3862	0.0559	0.0220	5.39
11	1116.5	1550.0	12.41	1.80	177.0	0.9563	0.3765	0.9728	0.3830	0.0561	0.0221	5.39
12	1116.5	1550.0	12.41	1.80	353.0	0.9581	0.3772	0.9954	0.3919	0.0589	0.0232	5.39
13	1144.3	1600.0	6.89	1.00	1153.0	0.9581	0.3772	1.0429	0.4106	0.0597	0.0235	4.86
14	1144.3	1600.0	6.89	1.00	411.0	0.9553	0.3761	0.9817	0.3865	0.0561	0.0221	4.86
15	1144.3	1600.0	8.27	1.20	260.0	0.9571	0.3768	0.9911	0.3902	0.0559	0.0220	4.86
16	1144.3	1600.0	8.27	1.20	385.0	0.9588	0.3775	0.9909	0.3901	0.0589	0.0232	4.86
17	1144.3	1600.0	8.27	1.20	300.0	0.9588	0.3775	1.0203	0.4017	0.0589	0.0232	4.86
18	1144.3	1600.0	8.27	1.20	512.0	0.9555	0.3762	0.9802	0.3859	0.0559	0.0220	4.86
19	1144.3	1600.0	9.65	1.40	498.0	0.9538	0.3755	1.0079	0.3968	0.0589	0.0232	4.86
20	1144.3	1600.0	9.65	1.40	344.0	0.9586	0.3774	0.9975	0.3927	0.0564	0.0222	4.86
21	1144.3	1600.0	11.03	1.60	255.0	0.9591	0.3776	0.9967	0.3924	0.0587	0.0231	4.86
22	1144.3	1600.0	12.41	1.80	156.0	0.9555	0.3762	0.9876	0.3888	0.0564	0.0222	4.86
23	1144.3	1600.0	12.41	1.80	162.0	0.9568	0.3767	0.9787	0.3853	0.0566	0.0223	4.86
24	1172.0	1650.0	8.27	1.20	183.0	0.9522	0.3749	0.9888	0.3893	0.0564	0.0222	4.29
25	1172.0	1650.0	8.27	1.20	195.0	0.9563	0.3765	0.9782	0.3851	0.0577	0.0227	4.29
26	1172.0	1650.0	12.41	1.80	79.0	0.9614	0.3785	1.0409	0.4098	0.0587	0.0231	4.29
27	1172.0	1650.0	12.41	1.80	76.0	0.9566	0.3766	1.0274	0.4045	0.0559	0.0220	4.29
28	1172.0	1650.0	12.41	1.80	57.0	0.9566	0.3766	1.0168	0.4003	0.0579	0.0228	4.29
29	1172.0	1650.0	12.41	1.80	40.0	0.9563	0.3765	0.9886	0.3892	0.0569	0.0224	4.29
30	1233.1	1760.0	5.52	0.80	51.0	0.9581	0.3772	1.0150	0.3996	0.0584	0.0230	2.38
31	1233.1	1760.0	5.52	0.80	59.0	0.9599	0.3779	1.0653	0.4194	0.0589	0.0232	2.38
32	1233.1	1760.0	12.41	1.80	7.0	0.9586	0.3774	1.0594	0.4171	0.0589	0.0232	2.38
33	1233.1	1760.0	12.41	1.80	5.0	0.9561	0.3764	0.9840	0.3874	0.0559	0.0220	2.38

TABLE III. - TEST RESULTS FOR TUBES OF RENE 41

Specimen	Equivalent stress, σ		Larson-Miller parameter, P (a)	Strain	Ultimate equivalent bore strain	Equivalent bore strain rate, ϵ_a , hr ⁻¹
	MN/m ²	ksi				
1	55.52	8.05	46.86	0.5395E-01	0.9513E-01	0.4607E-04
2	58.65	8.51	46.14	0.3510E-01	0.5204E-01	0.5795E-04
3	66.62	9.95	46.31	0.2957E-01	0.4381E-01	0.4008E-04
4	65.43	9.49	46.24	0.3913E-01	0.5871E-01	0.5830E-04
5	70.06	10.16	45.85	0.4206E-01	0.6311E-01	0.9740E-04
6	73.76	10.70	45.29	0.3930E-01	0.5818E-01	0.1706E-03
7	69.97	10.15	45.37	0.5351E-01	0.8032E-01	0.2148E-03
8	70.01	10.15	45.32	0.4845E-01	0.7272E-01	0.2054E-03
9	75.23	10.91	45.71	0.4667E-01	0.6991E-01	0.1264E-03
10	78.90	11.44	45.44	0.2278E-01	0.3369E-01	0.8299E-04
11	88.08	12.77	44.72	0.1726E-01	0.2559E-01	0.1446E-03
12	83.89	12.17	45.32	0.3897E-01	0.5851E-01	0.1657E-03
13	46.11	6.69	47.52	0.8855E-01	0.1334E+00	0.1147E-03
14	49.00	7.11	46.58	0.2765E-01	0.4100E-01	0.9976E-04
15	59.19	8.58	46.17	0.3556E-01	0.5264E-01	0.2025E-03
16	56.12	8.14	46.53	0.3338E-01	0.5010E-01	0.1301E-03
17	56.12	8.14	46.30	0.6411E-01	0.9622E-01	0.3207E-03
18	59.09	8.57	46.78	0.2578E-01	0.3818E-01	0.7457E-04
19	65.11	9.44	46.76	0.5672E-01	0.8527E-01	0.1712E-03
20	68.52	9.94	46.43	0.4054E-01	0.6013E-01	0.1748E-03
21	75.19	10.90	46.16	0.3919E-01	0.5876E-01	0.2304E-03
22	87.81	12.74	45.72	0.3349E-01	0.4972E-01	0.3187E-03
23	87.52	12.69	45.75	0.2283E-01	0.3392E-01	0.2094E-03
24	58.53	8.49	46.97	0.3841E-01	0.5707E-01	0.3119E-03
25	57.45	8.33	47.03	0.2284E-01	0.3410E-01	0.1749E-03
26	85.09	12.34	46.20	0.8269E-01	0.1239E+00	0.1568E-02
27	89.04	12.91	46.17	0.7408E-01	0.1097E+00	0.1443E-02
28	85.81	12.44	46.05	0.6293E-01	0.9407E-01	0.1404E-02
29	87.37	12.67	45.58	0.3373E-01	0.5018E-01	0.1255E-02
30	38.77	5.62	48.36	0.5938E-01	0.8894E-01	0.1458E-02
31	38.51	5.59	48.33	0.1098E+00	0.1648E+00	0.2793E-02
32	86.52	12.55	46.28	0.1052E+00	0.1579E+00	0.2256E-01
33	91.05	13.21	45.95	0.2922E-01	0.4327E-01	0.8654E-02

TABLE IV. - CREEP-RUPTURE DATA FOR SHEET SPECIMENS OF RENE 41

[From ref. 8.]

Specimen	Temperature,		Stress		Lifetime, hr	Strain	Strain rate, ε̇, hr ⁻¹	Larson- Miller param- eter, P (a)	
	T		MN/m ²	ksi					
	K	°F							
NEMO63	1005.4	1350.0	565.37	82.00	39.2	0.1600E-01	0.4082E-03	39.08	
	1005.4	1350.0	517.11	75.00	57.2	0.3200E-01	0.5594E-03	39.38	
	1005.4	1350.0	482.63	70.00	82.0	0.1000E-01	0.1220E-03	39.66	
	1005.4	1350.0	455.05	66.00	131.0	0.1000E-01	0.7634E-04	40.03	
	1005.4	1350.0	413.69	60.00	213.0	0.1500E-01	0.7042E-04	40.41	
	1005.4	1350.0	386.11	56.00	158.0	0.3200E-01	0.2025E-03	40.18	
	1005.4	1350.0	361.97	52.50	810.0	0.1400E-01	0.1728E-04	41.46	
	1005.4	1350.0	344.74	50.00	780.0	0.1500E-01	0.1923E-04	41.43	
	1088.7	1500.0	448.16	65.00	6.6	0.3600E-01	0.5455E-02	40.81	
	1088.7	1500.0	275.79	40.00	150.0	0.4500E-01	0.3000E-03	43.47	
	1088.7	1500.0	241.32	35.00	239.0	0.7000E-01	0.2929E-03	43.86	
	1088.7	1500.0	224.08	32.50	378.0	0.3200E-01	0.8466E-04	44.25	
	1088.7	1500.0	206.84	30.00	482.0	0.3600E-01	0.7469E-04	44.46	
	1088.7	1500.0	189.61	27.50	661.0	0.3100E-01	0.4690E-04	44.73	
	1172.0	1650.0	241.32	35.00	8.0	0.5000E-01	0.6250E-02	44.11	
	1172.0	1650.0	172.37	25.00	32.0	0.4000E-01	0.1250E-02	45.38	
	1172.0	1650.0	137.90	20.00	121.0	0.1500E-01	0.1240E-03	46.59	
	1172.0	1650.0	124.11	18.00	93.0	0.2400E-01	0.2581E-03	46.35	
	1172.0	1650.0	113.76	16.50	149.0	0.4800E-01	0.3221E-03	46.79	
	1172.0	1650.0	103.42	15.00	534.0	0.4800E-01	0.9524E-04	47.90	
	1172.0	1650.0	96.53	14.00	238.0	0.2700E-01	0.1134E-03	47.21	
	1172.0	1650.0	89.63	13.00	544.0	0.4400E-01	0.8088E-04	47.97	
	1172.0	1650.0	82.74	12.00	399.0	0.4100E-01	0.1054E-03	47.66	
	1172.0	1650.0	75.84	11.00	950.0	0.3400E-01	0.3579E-04	48.48	
	AVCO46	1172.0	1650.0	172.37	25.00	23.6	0.4300E-01	0.1695E-02	45.10
	AVCO25	1172.0	1650.0	172.37	25.00	21.6	0.2315E-02	0.2315E-02	45.02
	AVCO25	1172.0	1650.0	172.37	25.00	12.0	0.3300E-01	0.2500E-02	44.48
	AVCO42	1172.0	1650.0	172.37	25.00	46.0	0.1500E+00	0.3261E-02	45.71
LTV035	1195.8	1700.0	110.32	16.00	29.0	0.1850E+00	0.6379E-02	46.36	
	1195.8	1700.0	110.32	16.00	28.0	0.1780E+00	0.6357E-02	46.33	
	1195.8	1700.0	93.08	13.50	51.0	0.2380E+00	0.3410E-02	47.06	
	1195.8	1700.0	93.08	13.50	63.0	0.1910E+00	0.3032E-02	47.09	
	1195.8	1700.0	75.84	11.00	119.0	0.1640E+00	0.1378E-02	47.68	
	1195.8	1700.0	75.84	11.00	141.0	0.1450E+00	0.1028E-02	47.84	
	1255.4	1800.0	86.18	12.50	7.7	0.2299E+00	0.2299E-01	47.20	
	1255.4	1800.0	65.50	9.50	21.0	0.1870E+00	0.8905E-02	48.19	
	1255.4	1800.0	65.50	9.50	25.0	0.2060E+00	0.8240E-02	48.36	
	1255.4	1800.0	55.16	8.00	42.0	0.1850E+00	0.4405E-02	48.87	
	1255.4	1800.0	55.16	8.00	35.0	0.2340E+00	0.6686E-02	48.69	
	1255.4	1800.0	44.82	6.50	97.0	0.1890E+00	0.1948E-02	49.69	
	1255.4	1800.0	44.82	6.50	31.0	0.2320E+00	0.2549E-02	49.63	
PM093	1033.1	1400.0	427.47	62.00	89.0	0.9800E-01	0.1101E-02	40.83	
	1033.1	1400.0	427.47	62.00	113.0	0.1070E+00	0.9469E-03	41.02	
	1033.1	1400.0	427.47	62.00	129.0	0.1480E+00	0.1147E-02	41.13	
	1033.1	1400.0	427.47	62.00	118.0	0.8600E-01	0.7288E-03	41.05	
	1088.7	1500.0	289.58	42.00	91.0	0.1590E+00	0.1747E-02	43.04	
	1088.7	1500.0	289.58	42.00	93.0	0.1430E+00	0.1723E-02	42.96	
	1088.7	1500.0	289.58	42.00	38.0	0.1680E+00	0.1714E-02	43.10	
	1088.7	1500.0	289.58	42.00	97.0	0.1590E+00	0.1639E-02	43.09	
	1144.3	1600.0	193.05	28.00	53.0	0.1390E+00	0.2057E-02	44.75	
	1144.3	1600.0	193.05	28.00	56.0	0.2390E+00	0.3621E-02	44.95	
	1144.3	1600.0	193.05	28.00	51.0	0.1430E+00	0.2804E-02	44.72	
	1144.3	1600.0	193.05	28.00	55.0	0.1370E+00	0.2491E-02	44.79	
	1195.8	1700.0	117.21	17.00	45.0	0.1250E+00	0.2778E-02	46.77	
	1195.8	1700.0	117.21	17.00	48.0	0.2370E+00	0.4313E-02	46.83	
	1195.8	1700.0	117.21	17.00	55.0	0.2100E+00	0.3818E-02	46.96	
	1195.8	1700.0	117.21	17.00	37.0	0.1440E+00	0.3892E-02	46.59	
	1255.4	1800.0	58.61	8.50	72.0	0.2460E+00	0.3417E-02	49.40	
	1255.4	1800.0	58.61	8.50	57.0	0.1630E+00	0.2433E-02	49.33	
	1310.9	1900.0	34.47	5.00	25.0	0.3800E+00	0.1520E-01	50.50	
1310.9	1900.0	34.47	5.00	2.8	0.4260E+00	0.1521E+00	48.26		
MQC064	1144.3	1600.0	355.08	51.50	1.3	0.4300E-01	0.3077E-01	41.43	
	1144.3	1600.0	275.79	40.00	6.0	0.6000E-01	0.1000E-01	42.80	
	1144.3	1600.0	241.32	35.00	12.6	0.5000E-01	0.3968E-02	43.47	
	1144.3	1600.0	241.32	35.00	9.8	0.7000E-01	0.7143E-02	43.26	
	1144.3	1600.0	206.84	30.00	25.5	0.5000E-01	0.1961E-02	44.10	
	1144.3	1600.0	172.37	25.00	95.0	0.7000E-01	0.7368E-03	45.27	
	1255.4	1800.0	103.42	15.00	8.1	0.9000E-01	0.1111E-01	47.25	
	1255.4	1800.0	103.42	15.00	8.4	0.9300E-01	0.1071E-01	47.29	
	1255.4	1800.0	86.18	12.50	10.5	0.8000E-01	0.7619E-02	47.51	
	1255.4	1800.0	68.95	10.00	29.0	0.6000E-01	0.2069E-02	48.51	
	DM5006	1144.3	1600.0	206.84	30.00	0.8	0.1000E-01	0.1250E-01	41.00
		1144.3	1600.0	172.37	25.00	5.0	0.2000E-01	0.4000E-02	42.64
1144.3		1600.0	172.37	25.00	7.1	0.1000E-01	0.1408E-02	42.95	
1144.3		1600.0	165.47	24.00	8.0	0.1000E-01	0.1250E-02	43.06	
1144.3		1600.0	137.90	20.00	11.3	0.1000E-01	0.8850E-03	43.37	
1144.3		1600.0	206.84	30.00	7.2	0.1300E-01	0.1389E-02	42.97	
1144.3		1600.0	137.90	20.00	18.0	0.1300E-01	0.5556E-03	43.79	
1144.3		1600.0	103.42	15.00	20.0	0.1000E-01	0.5000E-03	43.88	
1310.9		1900.0	41.37	6.00	2.4	0.1900E+00	0.7917E-01	48.10	
1310.9		1900.0	41.37	6.00	5.5	0.1500E+00	0.2727E-01	48.95	
1310.9		1900.0	41.37	6.00	4.7	0.1200E+00	0.2553E-01	48.79	
1310.9		1900.0	34.47	5.00	7.5	0.2800E+00	0.3733E-01	49.27	
1310.9	1900.0	34.47	5.00	4.3	0.4000E-01	0.9302E-02	48.69		
1310.9	1900.0	34.47	5.00	7.9	0.1500E+00	0.1899E-01	49.32		
AL5025	1172.0	1650.0	172.37	25.00	13.0	0.2300E-01	0.1538E-02	44.55	
	AL5032	1172.0	1650.0	172.37	25.00	29.0	0.3000E-01	0.1034E-02	45.29
	AL5050	1172.0	1650.0	172.37	25.00	45.3	0.4400E-01	0.9713E-03	45.69
	AL5025	1172.0	1650.0	172.37	25.00	34.0	0.2300E-01	0.6765E-03	45.43
	AL5032	1172.0	1650.0	172.37	25.00	22.0	0.8000E-01	0.3636E-02	45.03
	AL5050	1172.0	1650.0	172.37	25.00	52.0	0.7300E-01	0.1404E-02	45.82
	AL5050	1172.0	1650.0	172.37	25.00	48.0	0.4300E-01	0.6958E-03	45.75
	AL5125	1172.0	1650.0	172.37	25.00	54.4	0.1570E+00	0.2886E-02	45.86
	AL5070	1172.0	1650.0	172.37	25.00	59.0	0.1170E+00	0.1983E-02	45.94
	AL5XXX	1172.0	1650.0	172.37	25.00	34.8	0.2410E+00	0.6925E-02	45.45

01 EXIT IN CREEP

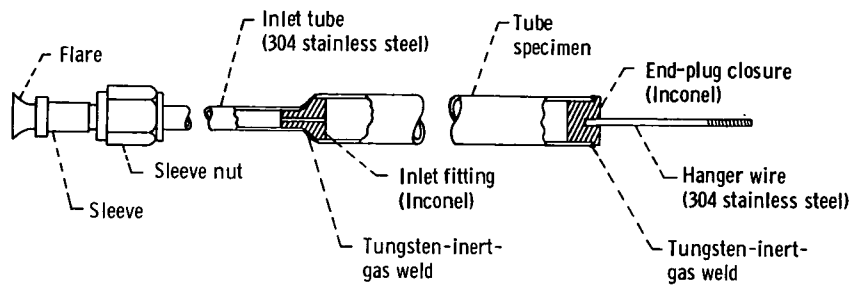


Figure 1. - Test specimen assembly.

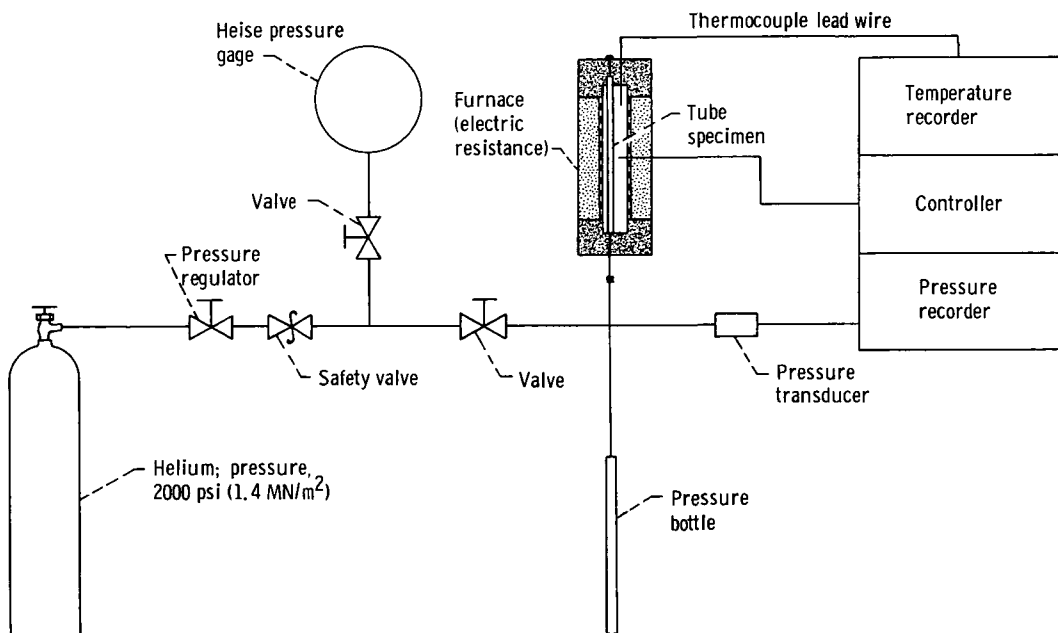


Figure 2. - Heat-exchanger-tube test rig. Maximum test temperature, 1233 K (1760° F); maximum test pressure, 12.41 MN/m² (1800 psi).

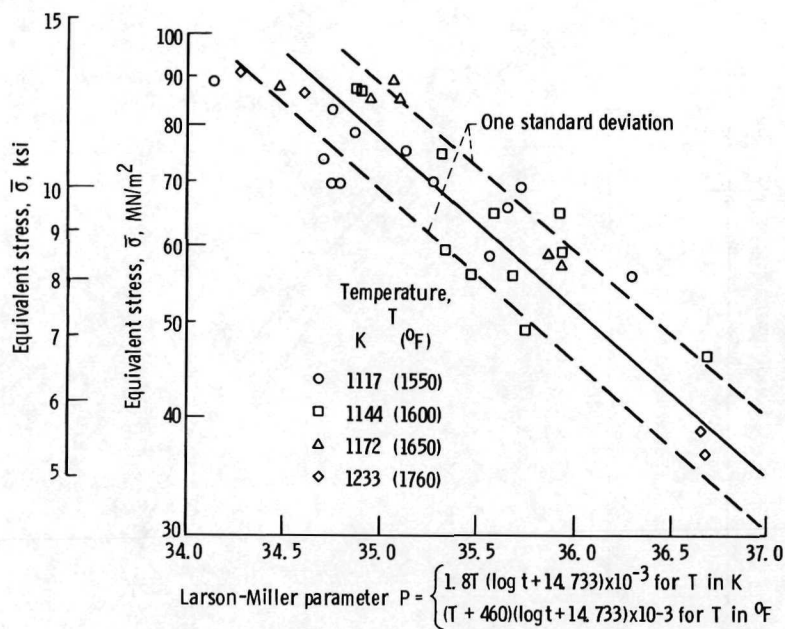


Figure 3. - Equivalent stress as a function of the Larson-Miller parameter for tube specimens of René 41.

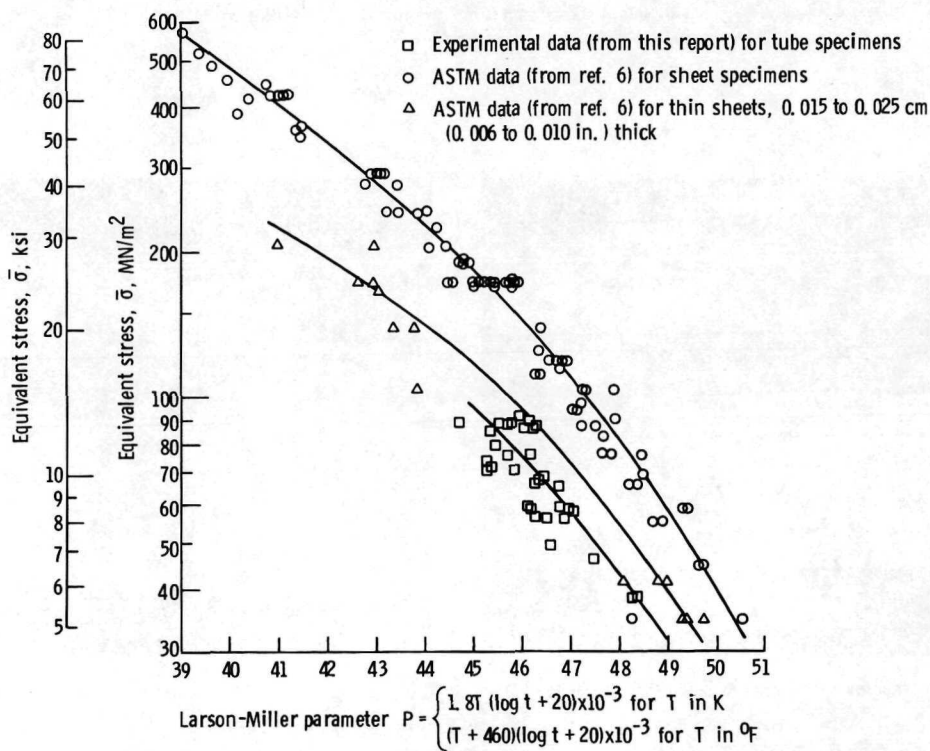


Figure 4. - Equivalent stress as a function of the Larson-Miller parameter for sheet and tube specimens of René 41.

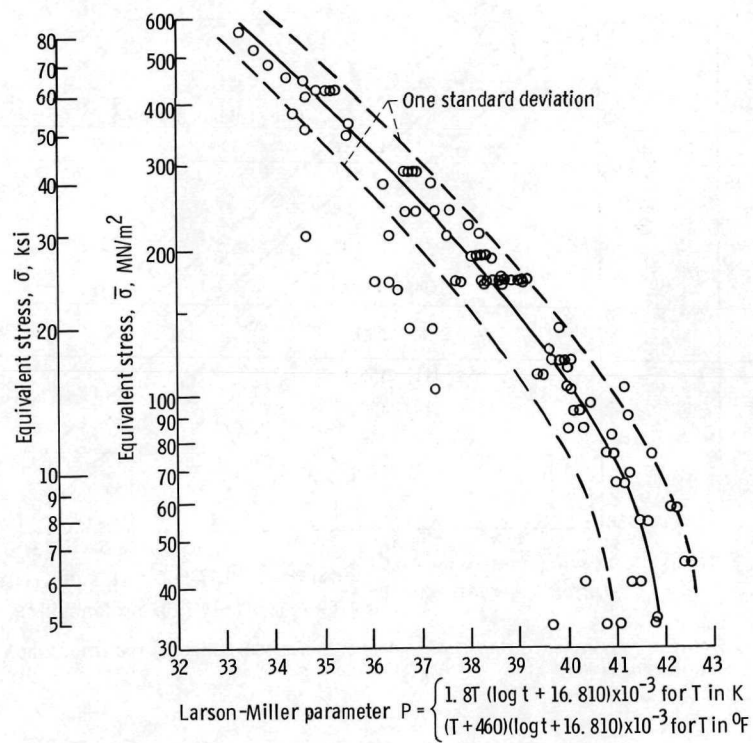
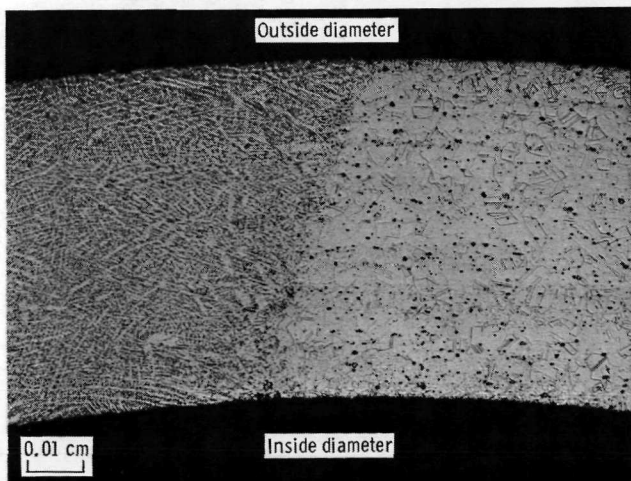
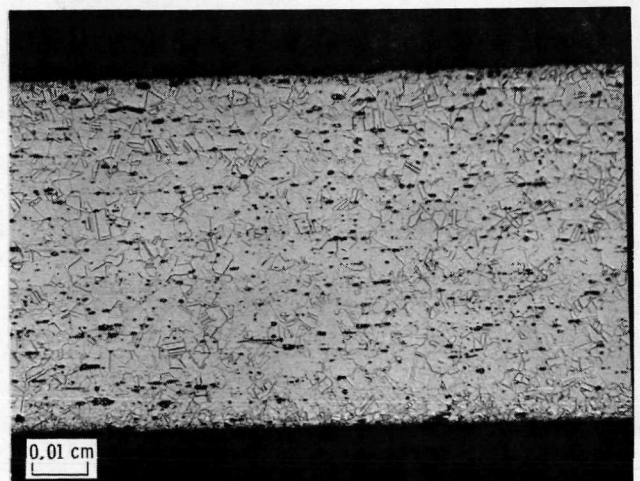


Figure 5. - Equivalent stress as a function of the Larson-Miller parameter for sheet specimens of René 41. (From ref. 6.)

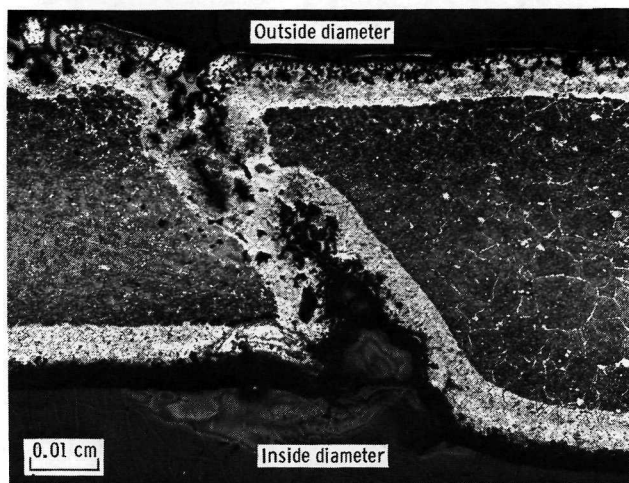


(a) Transverse section, showing weld area at left and parent metal at right.

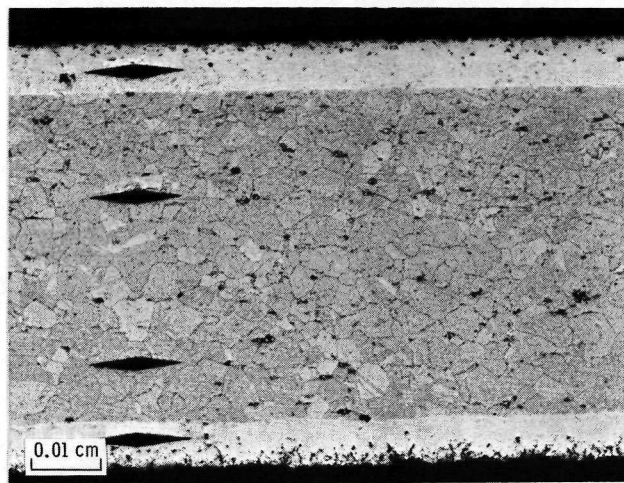


(b) Longitudinal section, showing parent metal.

Figure 6. - Sections of as-received tube specimens of René 41. Etched. X100.

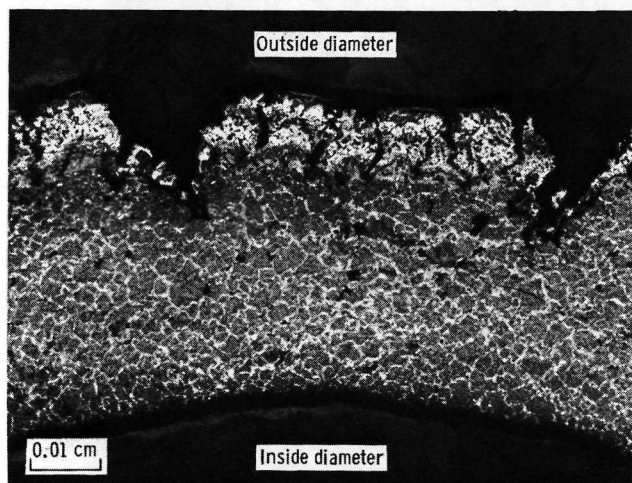


(a) Transverse section of failure area (weld).

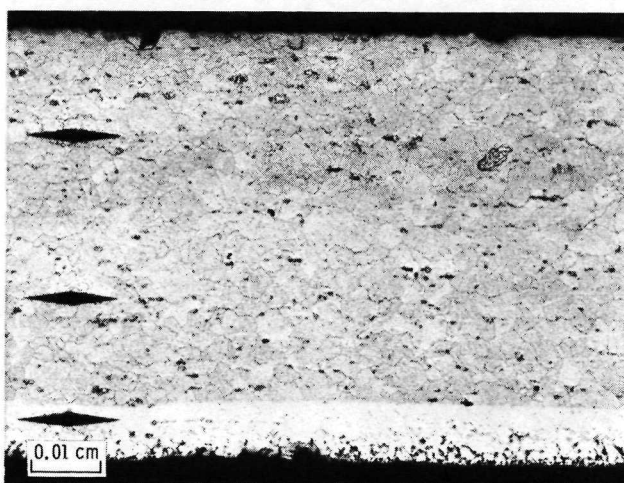


(b) Longitudinal section of parent metal.

Figure 7. - Section of tube specimen 25 after 195 hours at 1172 K (1650° F) and 8.27 MN/m² (1200 psi). Etched. X125.



(a) Transverse section of failure area (weld).



(b) Longitudinal section of parent metal.

Figure 8. - Sections of tube specimen 1 after 2065 hours at 1117 K (1550° F) and 7.93 MN/m² (1150 psi). Etched. X125.



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